By Rod Cross and Crawford Lindsey

What Do They Mean?

Editor's note: *Last month we promised more explanation of our findings that string power is not much affected by material, tension, or age of string. Explanation of this surprising conclusion begins on page 10, "Do Strings Ever Lose Power or Resiliance?" More explanation will follow next month.* ***Strings do affect power, but not for the reasons we previously thought!***

Last month we published the results of testing 89 different 16 gauge tennis strings.* This month we take a closer look at the data to see what it means. The tests involved measuring the physical properties of the strings. They were not playtests, so the tests were not designed to rank the strings in order of popularity or playability or even in any order from best to worst. The best string for one player might be the worst for another. Some players like soft strings and others prefer stiff strings. A rating from best to worst is therefore next to impossible. Nevertheless, strings can be rated in terms of physical properties such as tension loss, dynamic stiffness, durability, coefficient of friction, etc. One important property that was not measured in these tests was durability.

DYNAMIC STIFFNESS It Determines Almost Everything!

What Is Dynamic Stiffness? The most important physical property of a string is its *dynamic stiffness. The stiffness of a string tells us how far it will stretch when the string tension is increased.* The dynamic stiffness was measured after the string was tensioned to 28 kg (61.7 lbs). The string was left for 1000 seconds (16.7 minutes) to measure the loss in tension with time. It was then stretched rapidly by hitting it sideways with a hammer so that it stretched an extra 6 mm (1/4 inch) or so lengthwise. The string tension rose and fell within a period of about 30 ms (milliseconds, or thousanths of a second), at which time the hammer bounced off the string. We measured the increase in tension, DT, and the increase in length, DL. The dynamic stiffness, k, is given by k = DT/DL and it is measured in lb/in. For example, if the tension increases by 50 lb when an impact stretches the string lengthwise by 0.25 in, then k = 50/0.25 = 200 lb/in. This is a typical result for a nylon string. With a very stiff string like kevlar, the tension increased by about 120 lb when it was stretched by 0.2 inch, so k = 120/0.2= 600 lb/in. The softest string was natural gut, with k = 108 lb/in.

Measuring Dynamic Stiffness. We tested string samples of free length 320 mm (12.6 inch), held firmly in metal jaws. "Free length" is the distance between the jaws at the entry point of the string. A one pound hammer was swung into each string at a speed of 8.63 ft/sec to impact the middle of the string and to simulate the effect of serving a ball at about 120 mph. (The hammer weight and speed reproduced the impact energy calculated for one string's share of the impact of a 120 mph serve.) The hammer deflected the string sideways by about 1 inch, resulting in a lengthwise stretch of about 1/4 inch (note: sideways deflection and lengthwise stretch are not the same thing). The resulting measurement of k therefore refers to a string of length 12.6 inch. If we had tested a string twice as long, it would have stretched twice as far and k would have been half as stiff.

Quick Stretches vs Slow Stretches. Impacting a string with a hammer simulates the effect of hitting a tennis ball. It is not exactly the same, *but the important thing is the rapid stretch rather than a slow stretch*. During a slow stretch, such as when you string a racquet or when it is pulled slowly in a pull test machine, the string will keep stretching even if the tension is held constant. This phenomenon is known as creep. If the string has settled down at say 60 lb for a few days, then as soon as you increase the tension above 60 lb, the same thing happens. For example, if you increase the tension from 60 lb to 80 lb by pulling on the string, it will stretch immediately by a certain amount, but it keeps stretching forever at the higher tension. Measuring DT/DL under those circumstances obviously does not give a consistent measure of k. In order to get a reliable measurement of k without the effects of creep, it is necessary to stretch the string quickly (i.e., impact it instead of pulling it) and allow it to return quickly to its pre-stretch length before it has a chance to creep further.

On the first impact, a few molecular bonds get broken and the string stretches a bit further than usual. After that, it settles down and it is then possible to measure k reliably. That is why we impacted the string 10 times with the hammer. The dynamic stiffness varied a tiny bit from the 1st impact to the last, but usually by no more than 3%, despite the fact that each impact caused the string tension to drop immediately after each impact. To smooth out this variation in k, we took the average of all 10 impacts for every string tested.

Stiffness and Materials. *The dynamic stiffness of a string, for a lengthwise stretch, depends mainly on the type of material and not the tension*. However, all strings were tested at the same starting tension of 28 kg. We did not test the strings at other starting tensions, so we did not specifically look at a large range of different string tensions. However,

To view those results, go to RacquetTECH.com and click on articles.

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the tension dropped after each impact, and that allowed us to measure k over a small range of string tensions. The 3% variation in k over this small range of tensions for a given string was neglible compared with the 800% difference in k between gut and kevlar. We tested two gut strings and both had k = 108 lb/in. Kevlar strings ranged from 500 to 886 lb/in. Polyester strings ranged from k = 251 to 310 lb/in. Most of the strings we tested were nylon, and all had values of k between 161 and 225 lb/in. Only one zyex string was available, with k = 145 lb/in.

In terms of stiffness, this makes comparing one type of string with another relatively easy. Despite the fact that we tested 90 different strings, there were really only five catagories of string. In order of increasing stiffness they are gut, zyex, nylon, polyester and kevlar (aramid). *For a given material, different construction methods can make a small difference to the stiffness, but the biggest difference in stiffness comes when you switch to a different material.* Comparing one nylon with another is not so easy. The differences are not large, in which case other effects such as tension loss with time are then just as important in making the comparison.

IMPACT FORCE AND DURATION It's What You Feel

What Is It? *When a player hits the ball, each string in the racquet stretches by an amount that depends on its length and its dynamic stiffness.* The player is not actually aware of this and couldn't care less whether the center main stretches by 0.2 inch or 0.3 inch. The player is only aware of what is felt through the handle and what happens to the ball in terms of its flight path and spin.

The sound made by the strings and the ball is probably an important psychological effect, but it has no effect on the flight of the ball and only a tiny effect on the feel. Some players like both the sound and the feel of the strings vibrating, but the force transmitted to the handle by this vibration is tiny compared with the main impact force. The only reason players are aware of the string vibration at all is that the strings vibrate for about one second after the impact, while the frame vibrations die out much faster, in about 30 ms.

So, as far as the player is concerned, the most important effects of the strings are felt in terms of the impact force and the duration of the force. Both these effects depend on string tension and dynamic stiffness, which together, help determine string plane stiffness. But that's getting ahead of ourselves because the actual string plane stiffness depends on the number of strings in the racquet, the tension and the dynamic stiffness. But to begin to sort this out, we first need to look at the behaviour of a single string.

Measurements. The force on a single string and the impact duration (detailed last month for all 89 strings as the average of 10 impacts using the same hammer impacting at the same speed on every impact) both depend on string tension and dynamic stiffness in a way that is entirely predictable but very surprising. The force varies with time during an impact. It starts off at zero when the hammer (or a ball) first contacts the string, it increases to a maximum value when the string has stretched as far as it will go, then the force drops back to zero as the hammer bounces off the string. We measured only the maximum or the peak force as well as the duration of the force. (Actually, we measured the increase in tension in the string and the sideways displacement of the string, but it is easy to calculate the sideways force from that data.)

The increase in tension and the peak force during an impact both increase as stiffness (k) increases. For example, on a gut string, the tension increased by 22 lb and the peak force was 28 lb. On a kevlar string, the tension increased typically by about 100 lb and the peak force was typically about 44 lb. The impact duration was about 31 ms on gut and about 24 ms on kevlar.

Explanations. These numbers might look a bit strange at first sight. Kevlar is about 6 times stiffer than gut and the tension rises about 5 times more, but the peak force is only 50% larger and the impact duration is only about 20% shorter. Why is this? If kevlar is 6 times stiffer than gut, why isn't tension rise and peak force 6 times more and impact duration 6 times less?

Kevlar is very stiff, so it doesn't deflect very far when hit by the hammer. Being so stiff, only a small deflection of the string causes the tension to increase dramatically, more than doubling the initial tension. But the tension is directed along the string, not perpendicular in the direction of impact. Consequently, a very large increase in tension along the length of the kevlar string, combined with a small sideways deflection, results in a relatively small force acting in the direction of the impact. The force on the hammer is only about 50% larger with a stiffer string than the force on a gut string. The net result is that though the peak force on the kevlar string is larger (50% larger), that force acts for a shorter time (20% shorter) and the hammer is ejected at exactly the same speed for both strings.

Impact force and duration will cause different strings to feel differently with respect to shock and feel, but they both conspire to eject the hammer at the same speed from each of the different strings.

CALCULATIONS

Strings Do Not Lose Much Energy. All of these effects agree with detailed calculations of what should happen. What we didn't know before we did the tests was how well the strings would survive after repeated impacts of the hammer. *We expected that some would survive better than others and that some would lose their elasticity or resiliance after a sufficient number of impacts.*

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After 200 impacts on a nylon string, we gave up. None of the strings lost any of their resiliance or elasticity. They all lost tension after 10 impacts, but the hammer kept bouncing off every string at between 95% and 98% of the incoming speed for all of the strings. Each hammer impact lasted about 30 ms, which is six times longer than the normal 5 ms impact of a tennis ball on the strings. Two hundred hammer impacts is therefore equivalent in effect to 1200 normal impacts, each equivalent to a 120 mph serve.

If a string loses no energy during an impact, then the hammer will bounce off the string with exactly the same speed as the incoming speed. In fact, we found that the energy loss was not zero, but it was close enough to zero to make no significant difference in the calculations.

We did not test strings at tensions other than the starting tension of 62 pounds, but we did do some calculations to predict the results. (Actually, our impact tests tested strings at tensions ranging from 34 to 62 pounds because each string was at a different tension at impact depending on how much static and impact tension it had lost.) The calculations agree with last month's experimental results and are shown in Figures 1–4, pages 8 and 10 and are explained below.

Deflection: Perpendicular vs Linear Stiffness (or Deflection Stiffness vs Pulling Stiffness). As the graphs demonstrate, *the sideways deflection of the string is smallest for stiff strings and largest for soft strings, but it does not vary by as much as one might expect for different strings, nor does it vary much by changing tensions.* For example, if tension is 55 lb, then the string deflects by 29 mm for gut and about 22 mm for a kevlar string. The sideways deflection increases at lower string tensions, but only by 1 or 2 mm (figure 1). Intuitively, one might expect the deflection to double when the tension is halved, but this is not the case. *The reason is that the string gets stiffer, in a direction perpendicular to the string, the more it deflects.*

Strings act a bit like ordinary springs in that the harder you pull, the more they will stretch. But there is a difference. The stiffness of an ordinary spring doesn't change when you stretch it. If you pull a spring twice as hard it will stretch twice as far. If you pull or push *sideways* twice as as hard on a string, the string doesn't move twice as far. It moves less than this. The sideways stiffness is proportional to the string tension, so when the string is pushed sideways, the string stretches and the tension increases so the stiffness also increases. The lengthwise stiffness might also increase a bit, but this is a relatively small effect. In our impact tests, the lengthwise stiffness did not change significantly when we stretched each string.

Relationship of Deflection, Force, Tension. *If a string is subject to a sideways impact, the increase in tension, when the tension is low, is larger than that when the string is initially at a high tension (Figure 2). The reason is that when a string starts off at high tension, it is already fairly stiff in a sideways direction. The hammer comes to rest fairly quickly with only a relatively small stretch and a small increase in tension. If a string starts off at a low tension, the hammer pushes the string*

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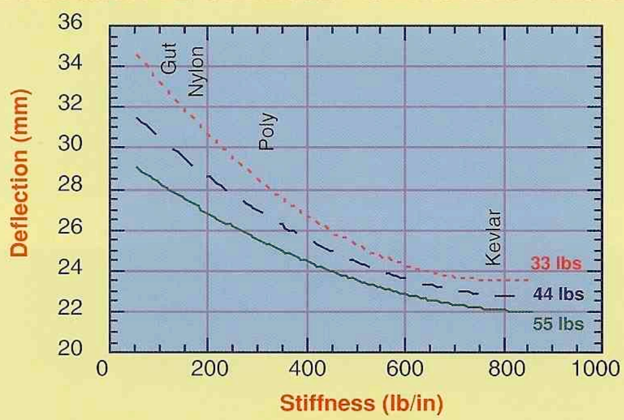
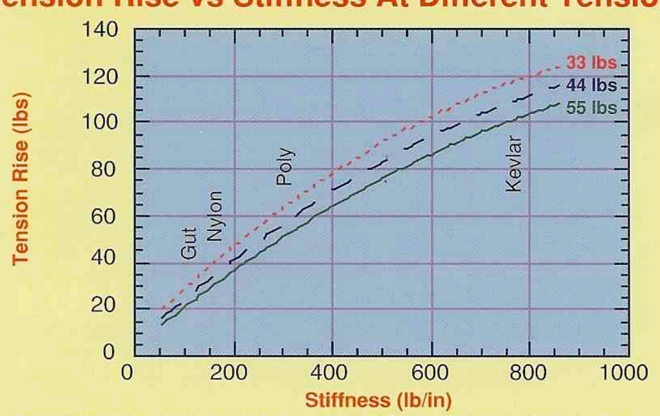
Deflection vs Stiffness At Different Tensions



Deflection increases when tension is lowered for a given string. The stiffer the string the less extra deflection you will get by lowering tension.

Figure 1

Tension Rise vs Stiffness At Different Tensions



Impact tension rises more for a string at lower tension compared to higher tension. The stiffer the string, the greater that difference.

Figure 2

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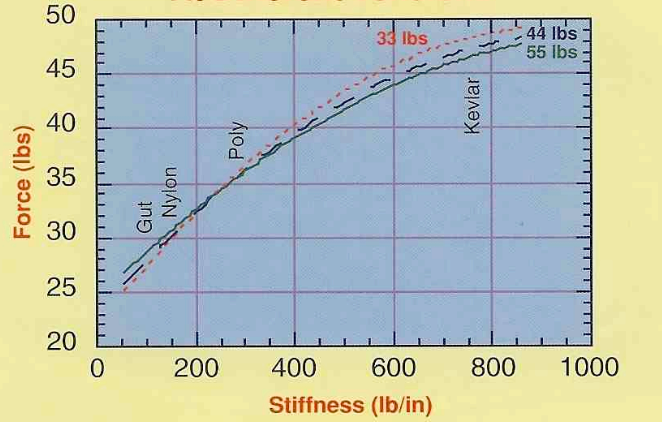
Force vs Stiffness At Different Tensions



For a string of any given stiffness, peak force does not change much by varying starting tension. A higher tension does not significantly increase the force on the string, nor does a lower one lessen it much.

Figure 3

Impact Duration vs Stiffness At Different Tensions

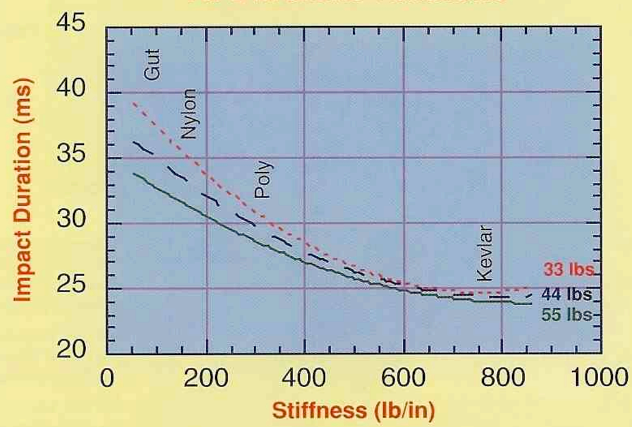


Figure 4 Impact duration is more significantly increased by lowering tension for soft strings than for stiffer strings.

a relatively long way before it comes to rest. As a result, the peak tension is only slightly smaller if you start with a string at low tension.

Furthermore, the peak force on any given string hardly varies at all if you change the initial tension. The peak force increases if you use a stiff string such as kevlar, but it doesn't really matter if you string kevlar at 33 lbs or 55 lbs. The peak force on the strings will be about the same. The same is true of nylons, polys and gut. *Regardless of the initial tension, or the subsequent loss in tension over time, the peak force on the string will be about the same. New and old strings should therefore feel much the same when measured in terms of the peak force on the strings. The main difference in feel between new and old strings will probably be due to the impact duration, which is longer on old strings at low tension. Is that the only difference? What about power?*

DO STRINGS EVER LOSE POWER OR RESILIANCE?

Difference Between New and Old Strings. Most players report that new strings perform better than old strings. New strings are crisper and give better ball control, while old strings are less lively and are often described as "dead." By dead, most players seem to mean that old strings lack the power of new strings. However, some players say the opposite, that they get more power out of the strings as they get older. New strings are at high tension and old strings are at a lower tension. Most players will tell you that strings lose their resiliance with age or use. But our tests show that they don't. It is possible that strings will lose resiliance if they are stretched almost to the breaking point, but we didn't stretch the strings that far. We stretched them only as far as they stretch in a 120 mph serve. *So we are left with some really tough questions here. Do old strings actually lose power or don't they? If they do, then how come the hammer keeps bouncing off at the same speed after lots of impacts? If they don't, then how come most players think they do?*

Steel Ball Drop Test. Further tests were done to look at this. A two pound steel boule was dropped from a height of 100 inches onto the strings of several racquets, with old and new strings, with the racquet clamped to the floor. The ball was held by an electromagnet so that it could be more easily dropped in the middle of the strings. The ball bounced to a height of between 89.7 and 90.3 inch off all the strings. This variation is too small to make any practical difference. So, that settles it. *Old strings DON'T lose power and they don't lose resiliance. They absorb all of the impact energy of a hammer or a steel ball and give most of it back, regardless of how old they are.* The ball bounced off

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the strings at 95% of the incoming speed, exactly the same as when the hammer bounced off a single string.

PLAYER PERCEPTIONS OF POWER

When a player says that new strings give more power than old strings, it is not a comment based on any accurate measurement, but rather a perception of power. The player might genuinely think the ball is coming off the strings faster when in fact it is not. How can this be possible? That is something I can't answer and I'm not even certain it is true, but there is clearly a difference in what players experience and what the above measurements and calculations are telling us. Some suggestions are as follows.

Old Strings Are Looser and Have MORE Power. We know that strings lose tension with time and with use. We also know that if you want more power you should string at a lower tension. That's because the strings will absorb more of the impact energy and the ball will absorb less, so less energy will be wasted in the ball. At least, that's the case with a tennis ball. A steel ball doesn't compress as much and loses no energy. That's why the steel ball was used to test the strings. *But this tells us that old strings will have MORE power than new strings when they are used to hit a tennis ball. That's a bit embarrassing. We can't use that argument to explain why old strings seem to have LESS power.*

Effect of Impact Duration on Power and Control. Perhaps there is a clue in the difference in impact duration between old and new strings. A ball or a hammer will spend more time on a soft string than a stiff string. So, as a string ages and the tension drops, the ball will spend more time on the strings. And though it will still come off at the same speed (maybe even a slightly higher speed if we believe that low tension = more power, which we will discuss next month) it will come off at a different angle. Why?

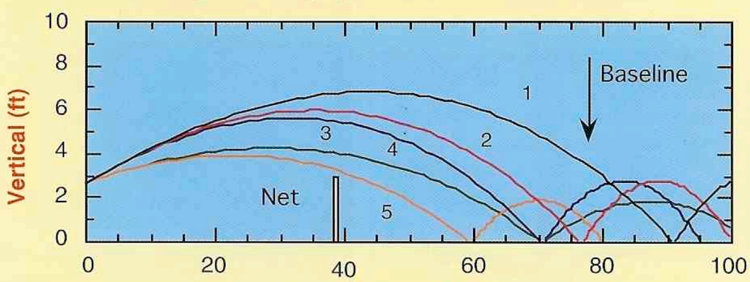
On strings at high tension, the ball will come off the strings after about 4.5 ms. With strings at low tension, the ball comes off after about 5 ms. For a serve or a smash, the racquet head swings through an angle of about 8 degrees in 4.5 ms or about 9 degrees in 5 ms, depending on how fast the racquet is swung. For a groundstroke, where the racket is swung at a slower speed, the racquet will swing through an angle of only 3 or 4 degrees during the time the ball is on the strings. A one degree change in the rebound angle means that the ball will land in a different spot, but a good player should be able to compensate by hitting the ball a bit earlier, one degree before the usual impact point. Nevertheless, if a player finds that the ball lands in a different spot, the question is whether the player will perceive this as a change in ball speed or a change in rebound angle. However, we don't think this is the effect we're looking for.

Psychological Effects: Is Power All In Your Head? Perhaps there are psychological effects involved here as well. If a ball stays on the strings for only a short time before it bounces off, then players might assume that it also comes off at higher speed because it came off faster. The word faster is ambiguous itself. Faster can mean sooner or it can mean higher speed. Players sometimes complain that pressureless balls are like bullets since they come off the strings so fast. They might spend a shorter time on the strings, but that doesn't mean they come off at a higher speed. Suppose a ball stays on string A for 4.5 ms and bounces off at 60 mph. On string B, it might stay on the string for 5.0 ms and still bounce off at 60 mph. But the player might think it came off at a higher speed from string A because it came off sooner and felt crisper. We are only guessing here. No one has done an experiment with a radar gun to check this out, but it might actually be true. There is definitely nothing wrong with the physics of this. *The speed off the strings depends on the force acting on the ball as well as the duration of the force. A small force acting for a long time can generate the same speed as a big force acting for a short time.* That's exactly what we measured with the hammer bouncing off different types of string.

Sound and Power. The sound of the impact might also play psychological tricks. If you hit a drum at high tension, you get a crisper sound than at low tension. If you use a string dampener, the shot sounds different (better for some and worse for others), but it can't make any difference to the speed of the ball since only a microscopic amount of energy is involved in the string vibrations.

Strings Don't Lose Power, They Lose Trajectory. There is

Trajectories, Spin and Shot Placement



1 = 70 mph, no spin, 10° 2 = 70 mph, 16 rps, 10° 3 = 70 mph, 28 rps, 10°

4 = 70 mph, no spin, 6° 5 = 70 mph, 16 rps, 6°

Note: the angles of 6 and 10 degrees are the launch angles above the horizontal.

another possible reason why old strings might seem to lose power when in fact they don't. Suppose you pick up a racquet with new strings and hit the ball consistently over the net to land on the baseline. Then you pick up the same model racquet but with older or well-used strings. If you play the same shot and the ball keeps landing short or in the net, what will you conclude? Will you say the old strings have lost power? What if you have to hit the ball a lot harder to get it over the net or onto the baseline? Will you still say that the old strings have lost power? You will probably answer yes to both questions. But suppose the ball comes off both sets of strings with exactly the same speed when you swing the racquet with the same speed. Then the strings have the same power, but the ball could come off the strings at a different vertical angle. *The ball might bounce off new strings at a higher angle than off old strings, possibly because new strings give a better grip on the ball than old strings. It might have something to do with the way the strings slide or don't slide across each other sideways in the string plane. That would explain why the ball clears the net with the new strings and lands short or in the net with old strings.*

The question now is, can a player judge the speed better than the vertical angle, or is it the other way around? Again, no one we know of has tested this with a radar gun, so we can't say for sure. Until that is done, we cannot give a definite answer to the question why old strings seem to lose power even though there is no loss of resiliance.

In the mean time, have a look at the ball trajectories in Figure 5. These were calculated on a computer.. The ball slows down through the air due to air resistance and lands on the court at a slower speed than when it was first hit. Can you guess which ball started off with the highest speed? Which one started off with the lowest speed?

The answers are that they all started at the same speed but the spin or the angle was different in each case. The trajectories are shown side-on. The player's view is from above and behind, so the angles won't be as easy to pick. A player might say "I'm not getting any power out of these strings," but a spectator might say, "The ball is coming off the strings at a low angle." Power describes ball speed, and control describes a consistent or expected ball angle. If the trajectories (4) and (5) are consistently low with old strings, and trajectories (1) - (3) are consistently high with new strings then control is good but it might seem that power is different. If the trajectories are not consistent, then the problem is with control, and that is probably a sign that the string tension is too low. At low tension, the ball stays on the strings a bit longer, giving the racquet more time to rotate about the long axis through the handle. If the ball strikes the strings off-axis then the racquet will rotate about the long axis and the ball will come off the strings at an angle that is either too low or too high depending on whether the ball strikes below or above the axis.